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ORIGINAL PAPER

The effect of fire disturbance on short-term soil respiration in typical forest of Greater Xing'an Range, China

Long Sun • Tongxin Hu • Ji Hong Kim • Futao Guo • Hong Song
Xinshuang Lv • Haiqing Hu

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Abstract: We investigated the effect of fire disturbance on short-term soil respiration in birch (*Betula platyphylla* Suk.) and larch (*Larix gmelinii* Rupr.) forests in Greater Xing'an range, northeastern China for further understanding of its effect on the carbon cycle in ecosystems. Our study show that post-fire soil respiration rates in *B. platyphylla* and *L. gmelinii* forests were reduced by 14% and 10%, respectively. In contrast, the soil heterotrophic respiration rates in the two types of forest were similar in post-fire and control plots. After fire, the contribution of root respiration to total soil respiration was dramatically reduced. Variation in soil respiration rates was explained by soil moisture (W) and soil temperature (T) at a depth of 5 cm. Exponential regression fitted *T* and *W* models explained *Rs* rates in *B. platyphylla* control and post-fire plots (83.1% and 86.2%) and *L. gmelinii* control and post-fire plots (83.7% and 88.7%). In addition, the short-term temperature coefficients in *B. platyphylla* control and post-fire plots were 5.33 and 5, respectively, and 9.12, and 5.26 in *L. gmelinii* control and post-fire plots, respectively. Our results provide an empirical baseline for studying the effect of fire disturbance on soil carbon balance and estimation of soil carbon flux in boreal forest.

Keywords: fire disturbance, short-term soil respiration, environment factors, Q_{10}

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Long Sun, Tongxin Hu, Hong Song, Xinshuang Lv, Haiqing Hu (✉)
College of Forestry, Northeast Forestry University, Harbin 150040, China. Email: hhq@nefu.edu.cn

Ji Hong Kim (✉)
Department of Forest Management, Kangwon National University, Korea. Email: kimjh@kangwon.ac.kr

Futao Guo
College of Forestry, Fujian Agriculture and Forestry University, Fuzhou, 350002, China.

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Introduction

Significant global climate changes are resulting in strong impacts on the carbon cycle in many ecosystems (Wang and Yang 2007; Luan et al. 2011). The emission of carbon dioxide from burning fossil fuels will lead to a steady rise in global temperature for the coming decades and centuries (Solomon et al. 2009). Terrestrial ecosystems are greatly affected by global climate change through dynamics of soil organic carbon. As an important component of the carbon cycle, soil respiration includes the sum CO_2 released by the respiration of plant roots, soil microorganisms and mycorrhizae (Borken et al. 2002). A large amount of carbon in soil is released to the atmosphere through soil respiration, which is the main pathway of transferring carbon from terrestrial ecosystems to the atmosphere (Bond-Lamberty and Thomson 2010; Comstedt et al. 2011). Soil carbon is also one of the main components of the global carbon balance (Buchmann 2000; Schlesinger et al. 2000), accounting for about 25% of the amount of global CO_2 exchange (Bouwmann et al. 1998). The amount of CO_2 released to the atmosphere through soil respiration is ten times greater than that resulting from the burning of fossil fuels (Rastogi et al. 2002; Davidson et al. 2006). The amount of CO_2 from global soil respiration is about 68Pg $C{\cdot}a^{-1}$, second only to the gross primary productivity (GPP) which fixes about 100–120 Pg $C{\cdot}a^{-1}$ (Raich and Schlesinger 1992). Small changes in soil respiration will cause great fluctuation in atmospheric CO_2 concentrations. Therefore, greater understanding of soil respiration dynamics is essential for understanding the global carbon bal-

ance (Jenkinson et al. 1991; Raich and Potter 1995; Chapin et al. 2002).

Forest ecosystems are important components of the entire terrestrial ecosystem. Carbon stocks in boreal forest ecosystems account for about 1/3–1/2 of total global carbon stocks or about 200–500 Gt of carbon, an important portion of the global carbon pool (Lehner et al. 2004). Moreover, the boreal forest ecosystem at high-latitudes is very sensitive to climate change (Piao et al. 2008; McGuire et al. 2009). High intensity forest fires often occur in boreal forests, and cause uncertainty in the global carbon balance (French et al. 2004). These are caused mainly by variation in soil characteristics at high-latitudes and environmental changes after fires. For example, the heterogeneity of fire behaviors due to wind direction, topography, and fuel levels (Hinzman et al. 2003; Kasischke et al. 2005; Rocha et al. 2011) causes significant post-fire changes to the main forest environmental factors, including temperature, soil water content, soil microorganism activity, and distribution of plant roots. All of these changes can dramatically affect soil respiration rates and tend to persist for long time periods after fire events (O'Neill et al. 2002; Flannigan et al. 2009).

Several studies have focused on the long-term measurement of soil respiration after fires (O'Neill et al. 2002; Czimczik et al. 2006; Tan et al. 2012). Fires, including crown fires, in high-latitude boreal forests damage the organic layer on the soil surface, leading to elevated surface temperatures and consequent thawing of the permafrost. As a result, the spatial variations in soil temperature and moisture are altered and this affects soil respiration. The extent of this effect depends on fire intensity and duration (O'Neill et al. 2003; Tan et al. 2012).

Only a few studies have assessed the short-term dynamics of post-fire soil respiration. Consequently our knowledge of the effect of fire disturbance on short-term soil respiration is limited. We lack a detailed understanding of the process of short-term soil carbon exportation and the driving factors and mechanisms. Therefore, it is especially difficult to develop a regional carbon cycle model to accurately estimate post-fire soil carbon emissions.

In the present study we quantified the dynamic changes in short-term soil respiration and soil carbon exportation after fires in *B. platyphylla* and *L. gmelinii* forests in the Greater Xing'an range of northeast China. Our study provides baseline data for developing carbon cycle models for post-fire forests in the Greater Xing'an range (the Daxing'anling mountains).

Materials and methods

Study area

This study was conducted in Gulian Forest Farm of Mohe county, Heilongjiang Province, China (52°10′N–53°33′ N, 124°07′ E–124°20′ E). The farm is located in the northern Greater Xing'an range and southern headwaters of Heilongjiang (Amur River in Russia). The Greater Xing'an range, the main forest area in northeastern China, is a fire-prone region. About 1614 fire events occurred in the Greater Xing'an range from 1965 to 2010 at an annual average of 35 fires. The total burned area over 45 years was nearly 3.52×10^6 ha and the annual average of area burned was 7.66×10^4 ha (Hu et al. 2012).

The study area has a temperate continental monsoon climate. It is cold and dry in winter, and humid and hot in summer. The annual average temperature is −5.5°C. The mean monthly temperature range is from –25.4°C (January) to 18.4°C (July). The annual average frost-free period is 86.2 days, and total precipitation is 460.8 mm. Gulian Forest Farm is dominated by *L. gmelinii* and *B. platyphylla*, and the main shrub-grass species are *Betula fruticosa* Pall., *Ledum palustre* L. var. *palustre*, and *Calamagrostis angustifolia* Kom.

Experimental design

Our sampling plots were established in a forest stand which experienced a fire event on 8 May 2012. Post-fire plots were sampled in *B. platyphylla* and *L. gmelinii* forests. Adjacent unburned plots were chosen as control plots. Three standard plots of 20 m × 20 m for each forest type and the same number of control plots were demarcated for a total of 12 plots. The intensity of fire on 8 May 2012 was medium and uniform across the entire study area. The mortality rates of trees in the post-fire plots of *B. platyphylla* and *L. gmelinii* forest were 35% and 40%, respectively. The layers of leaf litter and semi-humus were fully burned but the layer below the semi-humus was not. The average smoked heights of *B. platyphylla* and *L. gmelinii* forests were 2.1 m and 2.9 m, respectively.

Measurement of soil respiration

To measure soil respiration flux we used portable equipment models LI-8100-103 and LI-8100 Automatic Measuring Systems for Soil Carbon Flux (Li-Cor Inc., Lincoln, NE, USA).

Measurement was started at the end of July 2012. Five SH-200PVC collarswith a diameter of 19 cm and a length of 8 cm were randomly installed in the selected plots. We inserted the PVC collars into the ground so that the top of the ring was 3 cm above the soil surface. The trench method was used to investigate soil heterotrophic respiration (*Rh*) (Bond-Lamberty et al. 2004).

Three 60 cm × 60 cm quadrats (sample plots) were built within a distance of 1–1.5 m outside the standard plots. A 45–50 cm deep trench was dug in each quadrat, and all fine roots were removed from the trench. The connections between plant roots and the cross-section of the trench were cut off. Two layers of plastic sheet were used to wrap the cross-section of the trench to prevent the connection between trench and any plant roots. The soil that had been dug out of the trench was placed back in the trench.

All of the living plants in each quadrat were carefully removed, and the PVC collars were inserted in each quadrat. The procedure of PVC setting in a quadrat was the same as in the standard plot. The first measurement was taken 24 h after placing the PCV in order to ensure the accuracy of data. Five measurements were

taken between July and November. Four measurements of soil heterotrophic respiration were taken between August and November, after all of the roots in each plot died.

At a depth of 5 cm, soil temperature (T) and voltage (V4) were measured using a temperature probe (p/n 8100-201) and a soil moisture probe (ECH20 EC-5; p/n 8100-202) in the process of measuring soil respiration. The V4 value was converted to the volumetric water content (W) as per the manufacturer's instructions.

Statistical analysis

Data were analyzed using SPSS 19.0 statistical software (SPSS Inc., Chicago, IL, USA). ANOVA was used to compare means. Generalized linear regression (exponential regression) was used to determine the relationship between soil respiration rate and soil temperature at a depth of 5 cm. A residual error test was performed to identify the goodness-of-fit of the regression models. According to the results of the goodness-of-fit test, the exponential regression model was suitable for the relationship analysis of soil respiration rate and soil temperature at 5 cm depth.

After transformation, the exponential regression can be described as a linear regression model:

$$Ln(Rs)=\alpha+\beta\times T+\varepsilon\times W+\omega\times T\times W \tag{1}$$

where Rs is the soil respiration rate ($\mu mol\cdot m^{-2}\cdot s^{-1}$), T the soil temperature (°C) at a depth of 5 cm, W the soil moisture at a depth of 5 cm (%), α the intercept of the multiple regression equation, and β, ε, and ω are the regression coefficients of soil temperature at a depth of 5 cm, soil moisture, and their interaction, respectively.

The Q_{10} indicates is a measure of the change in root respiration rate change as a consequence of increasing the temperature by 10°C. We use the following formula (2) to calculate the Q_{10} value:

$$Q_{10} = e^{10\beta} \tag{2}$$

where β represents regression coefficient of exponential function.

Results

A significant temporal change of short-term soil respiration rate (*Rs*) occurred in both control and post-fire plots of *B. platyphylla* and *L. gmelinii* forests (Fig. 1). *Rs* decreased with time. Maximum *Rs* values were recorded in July in both control and post-fire plots of *B. platyphylla* and *L. gmelinii* forests. Maximum *Rs* values of *B. platyphylla* forest control plots, *B. platyphylla* forest post-fire plots, *L. gmelinii* forest control plots, *L. gmelinii* forest post-fire plots were 19.5, 16.7, 24, and 18.5 times greater than minimum values, respectively. Minimum *Rs* values were recorded in November. The mean *Rs* in post-fire and control plots of *B. platyphylla* and *L. gmelinii* forests were 2.52, 2.82, 2.5 and 2.77 $\mu mol\cdot m^{-2}\cdot s^{-1}$, respectively. The mean short-term soil respiration rate in the post-fire *B. platyphylla* forest was 14% lower than in the unburned plots. *Rs* values in post-fire plots in July and August were significantly lower than in control plots. *Rs* values in September, October and November were similar in burned and unburned plots ($p < 0.05$). The mean short-term soil respiration rate in the post-fire *L. gmelinii* forest was 10% lower than in the unburned plots. The decrease occurred mainly in August and values were similar in the other months ($p > 0.05$).

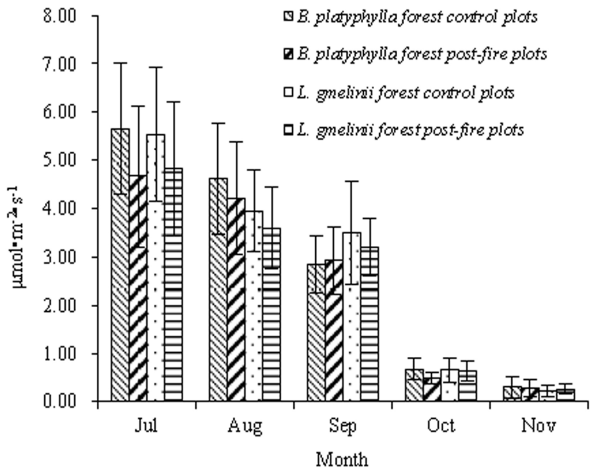

Fig. 1: Short-term soil respiration in burned and control plots in *B. platyphylla* and *L. gmelinii* forests

Maximum post-fire *Rh* was recorded in August in all plots, while minimum *Rh* was recorded in November. There was a significant seasonal dynamic for *Rh* in control and post-fire plots of *B. platyphylla* and *L. gmelinii* forests. Maximum *Rh* values of *B. platyphylla* forest control plots, *B. platyphylla* forest post-fire plots, *L. gmelinii* forest control plots, *L. gmelinii* forest post-fire plots were 17.2, 14.3, 18.6, and 13.8 times greater than minimum values, respectively. Mean *Rh* values in control and post-fire plots of *B. platyphylla* forest were 1.62 and 1.67 $\mu mol\cdot m^{-2}\cdot s^{-1}$, and in *L. gmelinii* forest control plots mean *Rh* was 1.56 $\mu mol\cdot m^{-2}\cdot s^{-1}$. *Rh* values from August to November differed significantly between the two forest types, and both decreased significantly beginning in October ($p < 0.05$). *Rh* values were similar in post-fire and control plots of *B. platyphylla* and *L. gmelinii* forests. Fig. 2 shows a distinct synchronous change in trends of *Rs* and *Rh* in post-fire plots. *Rs* was significantly greater than *Rh* during the growing season (from August to September, $p < 0.05$). However, there was no significant variation during the non-growing season (in October and November, $p > 0.05$).

RC values (the contribution of root respiration to soil respiration) in control and post-fire plots of *B. platyphylla* ranged from 23.1–30% and 12.5–25.5%, respectively, and in *L. gmelinii* forests, from 14.3–38.9% and 10.4–41.5%, respectively (Fig. 3). Monthly fluctuations of RC in each month in control and post-fire plots of *B. platyphylla* forest were not significantly. Compared to control plots, *B. platyphylla* forest RC values in burned plots showed the trend of decline of each month. Monthly

fluctuations of RC in control and post-fire plots of *L. gmelinii* forest were significantly different. Soil RC from October to November was greater than during the growing season (August-September) because soil *Rh* decreased more than soil autotrophic respiration (*Ra*) during the non-growing season. Although there was a significant change in short-term RC after fires in the two forest types, the pattern of change was not the same.

The result of model fitting indicated that *Rs* and *Rh* were significantly related to T after fire disturbance in both forest types (p <0.01). There were some differences in the relationships between *Rs, Rh* and *W*, and the interaction between *T* and *W* in the two forest types. In *B. platyphylla* forest, Rs and Rh were significantly correlated with *W*, whereas, in *L. gmelinii* forest Rs and *Rh* were not significantly correlated with W. In *B. platyphylla* forest, *Rs* was significantly correlated with the interaction between *T* and *W*, while Rh was not. In *L. gmelinii* forest *Rs* and *Rh* were significantly correlated with the interaction between T and W.

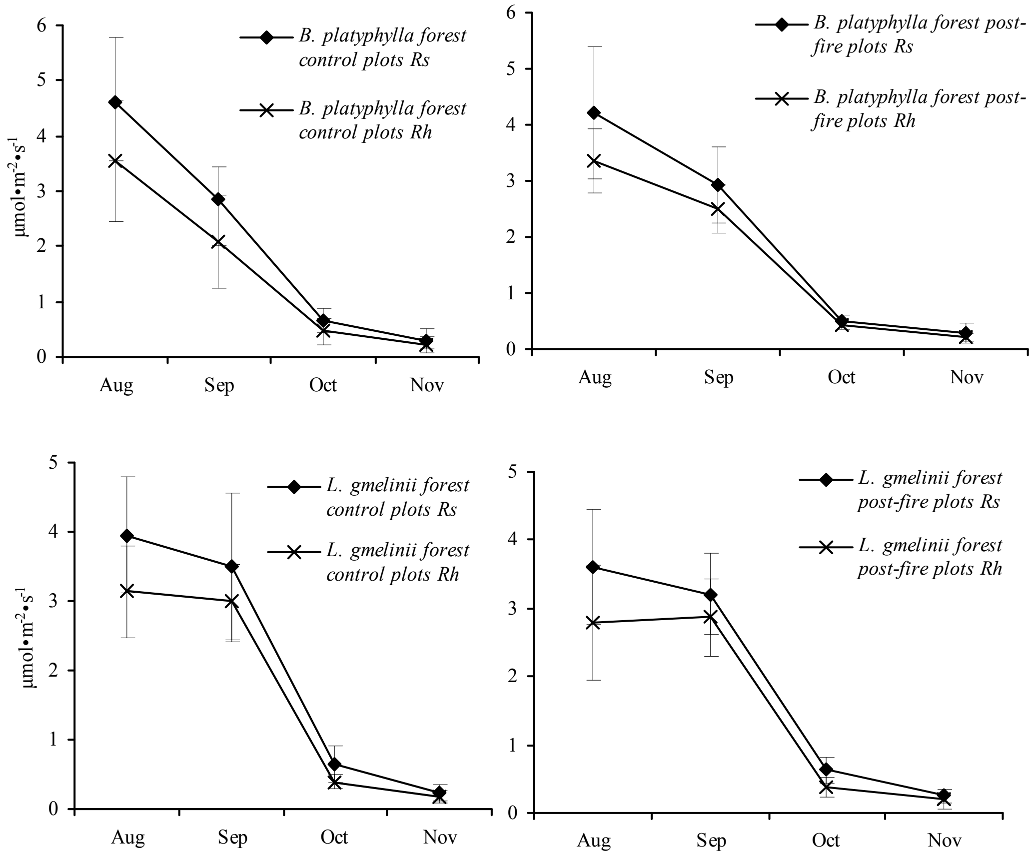

Fig. 2: Changes of short-term *Rs* and *Rh* after fire in control and post-fire plots of *B. platyphylla* and *L. gmelinii* forests.

Table. 1: The regression models with dependent variables of *Rs* or *Rh* and independent variables of *T* (soil temperature at a depth of 5 cm) or *W* (soil moisture) or the combination variable of *T* and *W* in control and post-fire plots of *B. platyphylla* and *L. gmelinii* forests

Plot type	Regression function	R^2	P
	ln(*Rs*)=−0.239+0.171×*T*	0.831	<0.0001
B. platyphylla forest control plots	ln(*Rh*)= −0.262+0.139×T−0.563×*W*	0.862	<0.0001
	Ln(*Rs*)=−0.739+0.161×*T*	0.862	<0.0001
B. platyphylla forest post-fire plots	ln(*Rh*)=−1.471+0.166×T+1.514×*W*	0.886	<0.0001
	ln(*Rs*)=−0.026+0.083×*T*+0.162×*T*×*W*	0.837	<0.0001
L. gmelinii forest control plots	ln(*Rh*)=0.829+0.158×*T*	0.888	<0.0001
	ln(*Rs*)=−0.409+0.096×*T*+0.094×*T*×*W*	0.887	<0.0001
L. gmelinii forest post-fire plots	ln(*Rh*)=0.501+0.187×*T*	0.761	<0.0001

Note: The fitted equations without significant contribution are omitted (p = 0.05)

The exponential regression-fitted *T* and *W* model explained 83.1% of the variation in *Rs* rates in *B. platyphylla* forest control

plots, 86.2% in *B. platyphylla* forest post-fire plots, 83.7% in *L. gmelinii* forest control plots, 88.7% in *L. gmelinii* forest post-fire plots (Table 1). The model explained 86.2% of the variation in Rh values in *B. platyphylla* forest control plots, 88.6% in *B. platyphylla* forest post-fire plots, 88.8% in *L. gmelinii* forest control plots, and 76.1% in *L. gmelinii* forest post-fire plots.

Our regression model of Q_{10}, the sensitivity of soil respiration to changing temperatures, was developed based on the function $Q_{10} = e^{10\beta}$ (Zhou et al. 2009). Q_{10} values for *Rs* in control and post-fire plots of *B. platyphylla* were 5.53 and 5.00, and in *L. gmelinii* forests values were 9.12 and 5.26.

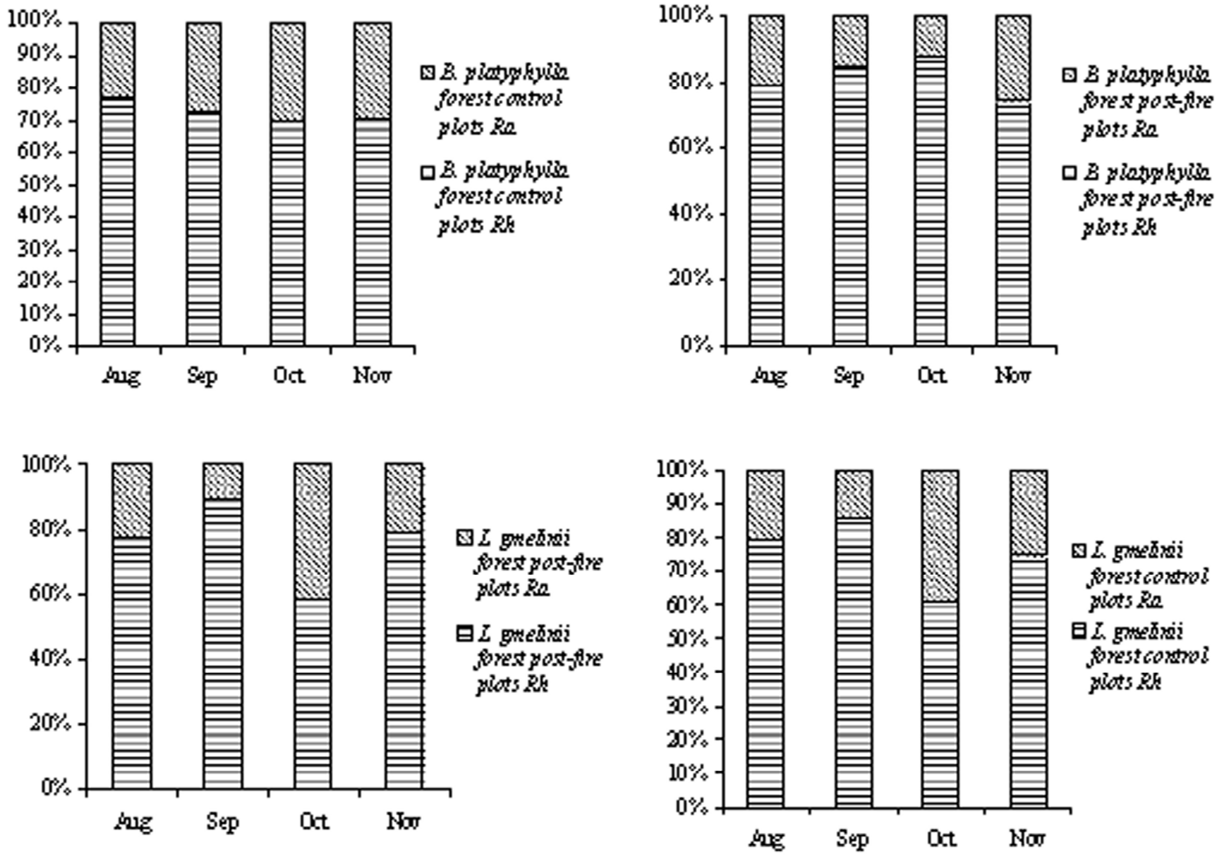

Fig. 3: Short-term RC in burned and unburned plots in *B. platyphylla* and *L. gmelinii* forests

Discussion

Our results were in agreement with the study of Zhang et al. (2008) which was conducted in *L. gmelinii* forests in the Greater Xing'an range at Genhe. The soil respiration rates of control plots in *L. gmelinii* forest at Nanweng River Ecological Orientation Station, Greater Xing'an Range, were 2.59–9.33 $\mu mol \cdot m^{-2} \cdot s^{-1}$, compared to 1.43–7.27 $\mu mol \cdot m^{-2} \cdot s^{-1}$ four years after a moderate intensity fire event (Tan et al. 2012). Both rates were greater than those recorded in this study. In addition, the soil respiration rates in this study were 4–5 times greater than those reported for a Siberian cedar forest (0.31–1.09 $\mu mol \cdot m^{-2} \cdot s^{-1}$) at high-latitude (Takakai et al. 2008). Vincent et al. (2006) reported that the range of soil respiration rates in temperate coniferous forest was 1–10 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The results of our study were consistent with other similar reports (He 2010; Jia 2006; Meng et al. 2011; Shi et al. 2012). Sawamoto et al. (2000) concluded that soil respiration declined by 46%–75% 1–5 years after fire in Siberia, and the extent of the impact of fire disturbance on soil respiration was determined by fire intensity and duration. O'Neill et al. (2002) reported that soil respiration declined by varying degrees in affected plots 7 years after fire. The thickness of the active soil, root damage in *Picea mariana* forest, and soil CO_2 flux increased due to the changes in soil temperature and the thawing of the permafrost (O'Neill et al. 2002). However, no dramatic change was recorded in soil respiration two years after fire in northern Canada. After 2 years, the soil respiration rate declined, and then rose to reach the pre-fire level within 7 years after the fire event (O'Donnell et al. 2009). Some authors reported that soil heterotrophic respiration rates increases after fire due to the decomposition of large amounts of combustible substances (Hicke et al. 2003; Tan et al. 2012). In this study, the correlation between soil heterotrophic respiration rate and

fire disturbance was not significant (p >0.05). One explanation might be that the organic layer on the soil surface and the litter were destroyed by fire, and the decline in soil heterotrophic respiration was only a short-term. In addition, the choice of time scale might be another reason explaining the absence of a significant difference (Hicke et al. 2003).

Our recorded increase in RC values during winter might have been caused by our use of the trench method. The trench method increased decomposition within soil respiration sampling quadrats this might have led to overestimation of soil heterotrophic respiration (Ngao et al. 2007; Wang and Yang 2007; Luan et al. 2011). Autotrophic respiration and heterotrophic respiration decrease simultaneously in winter but the decline in heterotrophic respiration is greater than for autotrophic respiration. This leads to higher estimated values for RC during winter. According to recent study, the seasonal dynamics of RC are affected by soil temperature and plant root phenology (Burton et al. 1998; Silvola et al. 1996). Richter et al. (2000) reported that soil respiration rates in post-fire plots were half of those in control plots in northern forests at the same latitude, largely because of the decline in soil *Ra* (Massman et al. 2010). Therefore, we inferred that the fire-caused damage to plants and roots was an important factor causing the decline in short-term soil respiration rate on our study area.

Soil temperature, soil moisture, and their interaction during the growing season are the main environmental factors influencing soil respiration (Högberg 2010; Ruehr et al. 2010). In the non-growing season, soil moisture remains stable, thus soil temperature is the main controlling factor of soil respiration rate (Tang et al. 2006; Zhou et al. 2009). After fire, soil temperature had an important impact on soil respiration in our two forest types because the litter and humus layers were burned, and more direct sunlight reached the soil surface. *L. gmelinii* forest was more sensitive to temperature than *B. platyphylla* forest. The leaf area index of *L. gmelinii* forest is lower than for *B. platyphylla* forest (Meng et al. 2011), especially when the canopy is partially combusted by fire.

The two forests differed in terms of soil water content. The influence of soil moisture in increasing short-term soil respiration in *B. platyphylla* forest after fires was significant, while there was no significant response in *L. gmelinii* forest. Similar results were reported by other authors (Orchard and Cook 2008; Rayment et al. 2000). However, the effect of soil water content on soil respiration rate varied by site. Some researchers (Liu et al 2002; Liu et al. 2009) concluded that since rain is abundant in northeast China, soil water content should be the main factor influencing soil respiration rates under extreme conditions. Thus, there is a possibility that the impact of water on soil respiration in this area is masked by temperature (Liu et al. 2009). The correlation between soil respiration and soil water content varies by forest type and environmental conditions. This might be due to the autotrophic respiration of roots (Zhou et al. 2007). Root respiration is greatly affected by the amount of photosynthesis occurring in the substrate and the factors that affect photosynthesis also impact root respiration (Ekblad et al. 2005; Högberg et al. 2001). *B. platyphylla* forest accounted for a greater root respiration proportion than in the *L. gmelinii* forest, and this may be the reason for the variation in response to soil water content between the *B. platyphylla* forest and the *L. gmelinii* forest.

The range of Q_{10} values during the growing season was reported by Ren et al. (2009) as 1.1–10. The range of variation was greater under cold conditions during the non-growing season (Mikan et al. 2002). Q_{10} is also affected by plant species, temperature, soil water content, nutrition status and the effectiveness of the respiratory substrate (Wang et al. 2010). Some enzymes related to aerobic respiration in plant roots or soil microorganisms may be inactivated due to high surface temperatures after fire, causing declines in soil respiration rates (Luo et al. 2006; Rochette et al. 1991). In this study, the Q_{10} of soil respiration in post-fire *B. platyphylla* and *L. gmelinii* forests declined by varying degrees. Q_{10} values for soil respiration in both control and post-fire *B. platyphylla* forests were lower than in *L. gmelinii* forest, in agreement with Mu (2004). Therefore, we infer that the change of Q_{10} of soil respiration may be closely related to plant root respiration. Any slight change in plant physiological activity would reflect the carbon distribution (Cronan 2003). Fire is a strong disturbance factor that affects plant physiology. The ratio of coarse roots to fine roots would be changed by fire disturbance, and this would strongly impact the temperature sensitivity of roots. Ren et al. (2009) reported that the temperature response of coarse roots and fine roots is different. Considering the complexity of determining the factors that influence Q_{10}, further work needs to be done.

Conclusions

Soil respiration rates in post-fire *B. platyphylla* and *L. gmelinii* forests declined by 14% and 10%, respectively. RC values for post-fire plots declined significantly compared to those in control plots for both forest types. This showed that the autotrophic respiration rate declined in both forest types. Short-term damage to roots might be one important driver of the reduction in short-term soil respiration rate after fire. The response of soil respiration rate to temperature at a depth of 5 cm and soil moisture differed significantly between the two forests. Overall, soil temperature and soil water content were the main environmental factors affecting the soil respiration rates in this area. The short-term Q_{10} in both types of post-fire forest showed varying degrees of decline. The changed conditions of roots after fire need to be studied further to understand the effect on short-term Q_{10} in this area.

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